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Adaptive Control

Algorithms, Analysis and Applications

Second Edition

 Springer

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*To Lina, Leticia, Salima, Noushin
Vlad, Jessica, Rogelio, Azadeh and Omid*

*Ce qui est simple est toujours faux
Ce qui ne l'est pas est inutilisable*

*Paul Valéry
Mauvaises Pensées*

Preface

Adaptive control provides techniques for the automatic adjustment of control parameters in real time either to achieve or to maintain a desired level of control system performance when the dynamic parameters of the process to be controlled are unknown and/or time-varying. The main characteristic of these techniques is the ability to extract significant information from real data in order to tune the controller and they feature a mechanism for adjusting the parameters of either the plant model or the controller. The history of adaptive control is long, significant progress in understanding and applying its ideas having begun in the early nineteen-seventies. The growing availability of digital computers has also contributed to the progression of the field. The early applications provided important feedback for the development of the field and theoretical innovations allowed a number of basic problems to be solved. The aim of this book is to provide a coherent and comprehensive treatment of the field of adaptive control. The presentation takes the reader from basic problem formulation to analytical solutions the practical significance of which is illustrated by applications. A unified presentation of adaptive control is not obvious. One reason for this is that several design steps are involved and this increases the number of degrees of freedom. Another is that methods have been proposed having different applications in mind but without a clear motivation for the intermediate design steps. It is our belief, however, that a coherent presentation of the basic techniques of adaptive control is now possible. We have adopted a discrete-time formulation for the problems and solutions described to reflect the importance of digital computers in the application of adaptive control techniques and we share our understanding and practical experience of the soundness of various control designs with the reader. Throughout the book, the mathematical aspects of the synthesis and analysis of various algorithms are emphasized; however, this does not mean that they are sufficient in themselves for solving practical problems or that ad hoc modifications of the algorithms for specific applications are not possible. To guide readers, the book contains various applications of control techniques but it is our belief that without a solid mathematical understanding of the adaptation techniques available, they will not be able to apply them creatively to new and difficult situations. The book has grown out of several survey papers, tutorial and courses delivered to various audiences (graduate students, practicing engineers, etc.) in various countries, of the research in the

field done by the authors (mostly at Laboratoire d'Automatique de Grenoble, now the Control Department of GIPSA-LAB (Institut National Polytechnique de Grenoble/CNRS), HEUDYASIC (Université Technologique de Compiègne/CNRS), CINVESTAV (Mexico), GREYC (Caen) and the Laboratoire d'Automatique of EPFL (Lausanne)), and of the long and rich practical experience of the authors. On the one hand, this new edition reflects new developments in the field both in terms of techniques and applications and, on the other, it puts a number of techniques into proper perspective as a result of feedback from applications.

Expected Audience The book is intended as a textbook for graduate students as well as a basic reference for practicing engineers facing the problem of designing adaptive control systems. Control researchers from other areas will find a comprehensive presentation of the field with bridges to various other control design techniques.

About the Content It is widely accepted that stability analysis in a deterministic environment and convergence analysis in a stochastic environment constitute a basic grounding for analysis and design of adaptive control systems and so these form the core of the theoretical aspects of the book. Parametric adaptation algorithms (PAAs) which are present in all adaptive control techniques are considered in greater depth.

Our practical experience has shown that in the past the basic linear controller designs which make up the background for various adaptive control strategies have often not taken robustness issues into account. It is both possible and necessary to accommodate these issues by improving the robustness of the linear control designs prior to coupling them with one of the adaptation algorithms so the book covers this.

In the context of adaptive control, robustness also concerns the parameter adaptation algorithms and this issue is addressed in detail. Furthermore, multiple-model adaptive control with switching is an illustration of the combination of robust and adaptive control and is covered in depth in the new edition. In recent years, plant model identification in closed-loop operation has become more and more popular as a way of improving the performance of an existing controller. The methods that have arisen as a result are directly relevant to adaptive control and will also be thoroughly treated. Adaptive regulation and adaptive feedforward disturbance compensation have emerged as new adaptive control problems with immediate application in active vibration control and active noise control. These aspects are now covered in this second edition.

The book is organized as follows:

- Chapter 1 provides an introduction to adaptive control and a tutorial presentation of the various techniques involved.
- Chapter 2 presents a brief review of discrete-time linear models for control with emphasis on optimal predictors which are often used throughout the book.
- Chapter 3 is a thorough coverage of parameter adaptation algorithms (PAA) operating in a deterministic environment. Various approaches are presented and then the stability point of view for analysis and design is discussed in detail.

- Chapter 4 is devoted to the analysis of parameter adaptation algorithms in a stochastic environment.
- Chapter 5 discusses recursive plant model identification in open loop which is an immediate application of PAAs on the one hand and an unavoidable step in starting an adaptive controller on the other.
- Chapter 6 is devoted to the synthesis of adaptive predictors.
- Chapter 7 covers digital control strategies which are used in adaptive control. One step ahead predictive control and long-range predictive control are presented in a unified manner.
- Chapter 8 discusses the robust digital control design problem and provides techniques for achieving required robustness by shaping the sensitivity functions.
- Digital control techniques can be combined with the recursive plant model identification in closed loop to obtain an adaptive controller. These recursive identification techniques are discussed in Chap. 9.
- The issue of robustification of parameter adaptation algorithm in the context of adaptive control is addressed in Chap. 10.
- For special types of plant model structures and control strategies, appropriate parametrization of the plant model allows direct adjustment of the parameters of the controllers yielding so called *direct adaptive control schemes*. Direct adaptive control is the subject of Chap. 11.
- Indirect adaptive control which combines in real-time plant model parameter estimation in closed loop with the redesign of the controller is discussed in Chap. 12.
- Multimodel adaptive control with switching, which combines robust control and adaptive control, is discussed in Chap. 13 (new in the second edition).
- Rejection of unknown disturbances is the objective of adaptive regulation which is the subject of Chap. 14 (new in the second edition).
- Adaptive feedforward compensation of disturbances is discussed in Chap. 15 (new in the second edition).
- Chapter 16 is devoted to the practical aspects of implementing adaptive controllers.

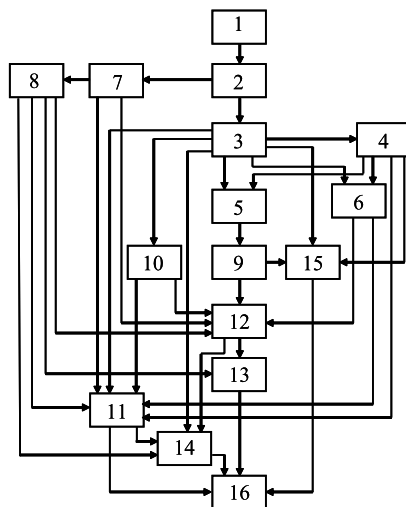
Chapters 5, 9, 12, 13, 14 and 15 include applications using the techniques presented in these chapters. A number of appendices which summarize important background topics are included.

Problems and simulation exercises are included in most of the chapters.

Pathways Through the Book The book was written with the objective of presenting comprehensive coverage of the field of adaptive control and of making the subject accessible to a large audience with different backgrounds and interests. Thus the book can be read and used in different ways.

For those only interested in applications we recommend the following sequence: Chaps.: 1, 2, 3 (Sects. 3.1 and 3.2), 5 (Sects. 5.1, 5.2, 5.7 through 5.9), 7 (Sects. 7.1, 7.2, 7.3.1 and 7.3.2), 8 (Sects. 8.1, 8.2 and 8.3.1), 9 (Sects. 9.1 and 9.6), 10 (Sect. 10.1), 11 (Sects. 11.1 and 11.2), 12 (Sects. 12.1 and 12.2.1), 13 (Sects. 13.1, 13.2 and 13.4), 14 (Sects. 14.1, 14.2, 14.4 and 14.7), 15 (Sects. 15.1, 15.2 and 15.5) and Chap.16. Most of the content of Chaps. 14 and 15 can also be

Fig. 1 Logical dependence of the chapters



read just after Chap. 3. The sequence above (till Chap. 15) can also serve as an introductory course in adaptive control.

For a more in-depth study of the field a course should include in addition the following Sects.: 3.3, 3.4, 4.1, 4.2, 5.3 through 5.6, 6.1, 6.2, 7.3.3 through 7.7, 8.3 through 8.6, 9.2 through 9.6, 10.2, 10.3, 10.4, 10.6, 11.4.1, 11.4.2 and 11.6, 12.2.2 through 12.3.1, 12.4 and 12.7, 13.3, 14.3, 14.5, 15.3 and 15.4. A graduate course in adaptive control might include all chapters of the book.

The material has been organized so that readers can easily see how the more technical parts of the book can be bypassed. Figure 1 shows the logical progression of the chapters.

The Website Complementary information and material for teaching and applications can be found on the book website: <http://www.landau-adaptivecontrol.org>.

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Grenoble, France

Ioan Doré Landau
Rogelio Lozano
Mohammed M’Saad
Alireza Karimi

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Abbreviations

Acronyms

a.s.	Almost sure convergence
ANC	Active noise control
ARMA	Auto regressive moving average
ARMAX	Auto regressive moving average with exogenous input
AVC	Active vibration control
FOE	Filtered output error algorithm
GPC	Generalized predictive control
CLOE	Closed loop output error recursive algorithm
EFR	Equivalent feedback representation
ELS	Extended least squares algorithm
FOL	Filtered open loop identification algorithm
G-CLOE	Generalized closed loop output error algorithm
GLS	Generalized least squares algorithm
IVAM	Instrumental variable with auxiliary model
LHS	Left hand side
MRAS	Model reference adaptive system
OE	Recursive output error algorithm
OEAC	Output error with adjustable compensator
OEEPM	Output error with extended prediction model
OEFC	Output error with fixed compensator
PAA	Parameter adaptation algorithm
PRBS	Pseudo random binary sequence
PSMR	Partial state model reference control
RHS	Right hand side
RLS	Recursive least squares algorithm
RML	Recursive maximum likelihood algorithm
SPR	Strictly positive real
X-CLOE	Extended closed loop output error algorithm

Notation

f_s	Sampling frequency
T_s	Sampling period
t	Continuous time or normalized discrete time (with respect to the sampling period)
$u(t), y(t)$	Plant input and output
$e(t)$	Discrete-time Gaussian white noise
$\hat{y}(t + j/t)$	j -steps ahead prediction of $y(t)$
q^{-1}	Backward shift operator ($q^{-1}y(t + 1) = y(t)$)
τ	Time delay (continuous time systems)
s, z	Complex variables ($z = e^{sT_s}$)
d	Delay of the discrete-time system (integer number of sampling periods)
$A(q^{-1})$	Polynomial in the variable q^{-1}
$\hat{A}(t, q^{-1})$	Estimation of the polynomial $A(q^{-1})$ at instant t
$\hat{a}_i(t)$	Estimation of the coefficients of the polynomials $A(q^{-1})$ (they are the coefficients of the polynomial $A(t, q^{-1})$)
θ	Parameter vector
$\hat{\theta}(t)$	Estimated parameter vector
$\tilde{\theta}(t)$	Parameter error vector
$\phi(t), \Phi(t)$	Measurement or observation vector
$F, F(t)$	Adaptation gain
$\hat{y}^0(t)$	A priori output of an adjustable predictor
$\hat{y}(t)$	A posteriori output of an adjustable predictor
$\varepsilon^0(t)$	A priori prediction error
$\varepsilon(t)$	A posteriori prediction error
$v^0(t)$	A priori adaptation error
$v(t)$	A posteriori adaptation error
$P(z^{-1})$	Polynomial defining the closed loop poles
$P_D(z^{-1})$	Polynomial defining the dominant closed loop poles
$P_F(z^{-1})$	Polynomial defining the auxiliary closed loop poles
A, M, F	Matrices
$F > 0$	Positive definite matrix
ω_0	Natural frequency of a 2nd order system
ζ	Damping coefficient of a 2nd order system
$\mathbf{E}\{\cdot\}$	Expectation
$R(i)$	Autocorrelation or cross-correlation
$RN(i)$	Normalized autocorrelation or cross-correlation